Wide spin resonance with an rf-bunched proton beam

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We recently used an rf solenoid to study the widths of rf spin resonances with both **unbunched** and **bunched** beams of 2.1 GeV/c polarized protons stored in the COSY synchrotron. A map, with **unbunched** beam at different fixed rf-solenoid frequencies, showed a very shallow possible depolarization dip at the resonance. Next we made frequency sweeps of 400 Hz, centered at similar frequencies, which greatly enhanced the dip. But, with a **bunched** proton beam, both the fixed-frequency and frequency-sweep techniques produced similar maps, and both **bunched** maps showed full beam depolarization over a wide region. Moreover, both were more than twice as wide as the **unbunched** dip. This **widening** of the **proton** resonance due to bunching is exactly opposite to the recently observed **narrowing** of **deuteron** resonances due to bunching.

The ability to preserve and precisely control a beam's polarization during acceleration and storage is needed to study the spin dependence of nuclear and particle interactions [1–5]. Rf magnets can induce rf spin resonances in storage rings, which allow one to manipulate the beam's polarization; they also allow detailed spin resonance studies and beam diagnostics. Running an rf magnet at different fixed frequencies or making small-range sweeps of its frequency near a spin resonance can produce a resonance map. Such maps can precisely determine the resonance's properties, such as its strength, width, central frequency, and frequency spread, as well as the beam's properties, such as its energy and its momentum spread. It was earlier discussed that bunching beams of muons [6, 7], electrons and positrons [8–10], or deuterons [11] could narrow a resonance's width and thus increase the measurements' precision. We recently used 2.1 GeV/c polarized protons stored in the COSY synchrotron for a detailed experimental study of both **unbunched** and **bunched** proton beam resonances.

In flat circular rings, each beam particle's spin normally precesses around the vertical fields of the ring's dipole magnets. The spin tune $\nu_s = G\gamma$ is the number of spin precessions during one turn around the ring; $G = (g-2)/2$ is the particle's gyromagnetic anomaly and γ is its Lorentz energy factor. A horizontal magnetic field can perturb the particle's stable vertical polarization creating a spin resonance [12–14]. Rf magnets can induce rf spin resonances [15–22]. A proton's rf-induced spin resonance's frequency is

$$f_r = f_c(k \pm G_p\,\gamma), \qquad (1)$$

where f_c is the proton's circulation frequency, k is an integer, and $G_p = 1.792\,847$.

The apparatus for this experiment, including the COSY storage ring [23–26], the EDDA detector [27, 28], the electron Cooler [29], the low energy polarimeter (LEP) [30], the injector cyclotron, and the polarized ion source [31–33] were shown in Fig. 4 of ref [34]. The beam

from the polarized H^- ion source was accelerated by the cyclotron to 45 MeV and then strip-injected into COSY. Before this injection, the LEP measured the H^- beam's polarization to monitor its stability.

The 24.5 keV electron Cooler reduced the beam's momentum spread $\Delta p/p$ by cooling it, both longitudinally and transversely, for 15 s at the protons' 45 MeV injection energy. The protons were then accelerated to 2.1 GeV/c, where the rf acceleration cavity was either **off** during COSY's flat-top giving an **unbunched** beam, or **on** giving a **bunched** beam.

A spin resonance was induced using an rf solenoid magnet [35]; it was a 25-turn air-core water-cooled copper coil, of length 57.5 cm and average diameter 21 cm. Its inductance was 41 ± 3 μH. It was part of an RLC resonant circuit, which operated near 902.6 kHz, typically at an rf voltage of 5.7 kV rms. The longitudinal rf magnetic field at its center was about 1.17 mT rms, giving an rf $\int Bdl$ of 0.67 $\pm$ 0.03 T·mm rms.

The cylindrical EDDA polarimeter [27, 28] then measured the beam's polarization in COSY. We reduced its systematic errors by cycling the polarized source between the up and down vertical polarization states. The measured flattop polarization, before spin manipulation, was typically about 75%.

In the COSY ring, the protons' average circulation frequency f_c was 1.491 85 MHz at 2.1 GeV/c, where their Lorentz energy factor was $\gamma = 2.4514$. For these parameters, the spin tune $\nu_s = G\gamma$ was 4.395. Thus, Eq. (1) gave that the $k = 5$ spin resonance's central frequency should be near

$$f_r = (5 - G\gamma)f_c = 902.6 \text{ kHz}. \qquad (2)$$

We first obtained the rf-induced spin resonance's strength ε experimentally [19–22]. The polarization was measured after ramping the rf solenoid's frequency through the resonance with various ramp times Δt, while the ramp's frequency range Δf and voltage were both fixed. We then fit these data to the modified [36]
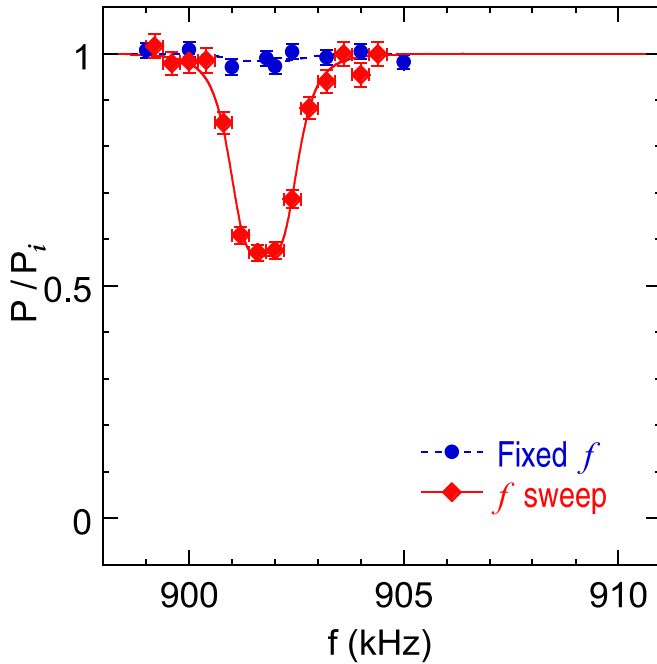
FIG. 1: Polarization ratio P/P_i, measured at 2.1 GeV/c with an **unbunched** proton beam, plotted vs the rf solenoid's central frequency f, where P and P_i are the final and initial vertical polarizations, respectively. The spin resonance strength $\boldsymbol{\varepsilon}$ at full rf-solenoid voltage was 31.3×10^{-6}. The rf solenoid's ramp-up and ramp-down times t_R were 200 ms; its on-time at full $\boldsymbol{\varepsilon}$ was $t_{ON} = 2$ s. The frequency sweep data's range was 400 Hz; its sweep time was 2 s. COSY's proton momentum spread is usually less than 10^{-3}. The curves are fits to empirical 2nd-order Lorentzians. The errors are purely statistical.

Froissart-Stora equation [12] with $\boldsymbol{\varepsilon}$ as a fit parameter to obtain $\boldsymbol{\varepsilon} = (31.3 \pm 0.1) \times 10^{-6}$.

A resonance map was then obtained with the beam **unbunched**. For different fixed rf-solenoid frequencies f near 902.6 kHz, we linearly ramped the rf solenoid's strength from zero to full $\boldsymbol{\varepsilon}$ during $t_R = 200$ ms; we then held $\boldsymbol{\varepsilon}$ fixed during $t_{ON} = 2$ s; next we linearly ramped it to zero during $t_R = 200$ ms. The resulting measured polarization ratios P/P_i are plotted in Fig. 1. Note that any possible depolarization dip is very shallow and the measured final polarization is almost consistent with its initial value. This is probably due to the proton beam's large momentum spread $\Delta p/p$ [37]. We fit these fixed-frequency **unbunched** P/P_i data to an empirical 2nd-order Lorentzian function obtaining $\chi^2/(N-3)$ of 0.9. The fit gave a central resonance frequency f_r of 901.8 ± 0.8 kHz and a width w of 2 ± 2 kHz FWHM. The large uncertainties in this fixed-frequency fit are due to the possible dip being very shallow.

To enhance the depth of the **unbunched** resonance and thus improve the precision of its frequency and width measurements, we made 400 Hz rf-solenoid frequency sweeps near the resonance. We again ramped the rf solenoid's strength from zero to full $\boldsymbol{\varepsilon}$ in 200 ms while
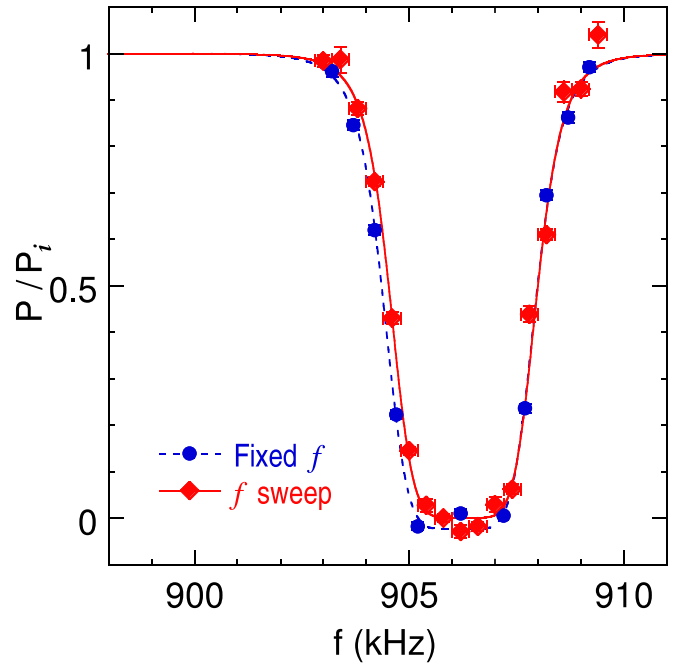

FIG. 2: Vertical polarization ratio P/P_i, measured at 2.1 GeV/c with a **bunched** proton beam, plotted vs the rf solenoid's central frequency f. The rf-solenoid parameters are in Fig. 1 caption; the beam's synchrotron frequency f_s was 56 Hz. The curves are fits to empirical 3rd-order Lorentzians.

holding its frequency fixed; we then ramped its frequency by 400 Hz in 2 s; we next ramped $\boldsymbol{\varepsilon}$ down to zero while again holding the frequency fixed. We made many such sweeps adjacent to one another to cover the entire resonance range. The resulting data are plotted against the sweeps' central frequencies in Fig. 1 along with the fixed-frequency data. Each point's frequency-sweep range is indicated by a horizontal bar.

As seen from Fig. 1, the frequency-sweep technique greatly enhanced the **unbunched** map's depolarization dip allowing a precise determination of the resonance's location and width. Fitting the frequency-sweep data in Fig. 1 to a 2nd-order Lorentzian yielded f_r of 901.7 ± 0.2 kHz and w of 1.7 ± 0.2 kHz FWHM with $\chi^2/(N-3)$ of 0.8. Note that the errors in f_r and w are dominated by the frequency-sweep's ± 200 Hz size. Averaging the fixed-frequency and frequency-sweep results gave $f_r = 901.7 \pm 0.2$ kHz and $w = 1.7 \pm 0.2$ kHz FWHM for **unbunched** beam.

We next used the procedure described above to obtain fixed-frequency and frequency-sweep maps of a **bunched** proton beam with a synchrotron frequency f_s of 56 Hz. These data are shown in Fig. 2 using the same scale and notation as in Fig. 1. We fit both Fig. 2 resonance maps to empirical 3rd-order Lorentzians. For the fixed-frequency map, the fit gave f_r of 906.17 ± 0.02 kHz and w of 3.61 ± 0.04 kHz FWHM with $\chi^2/(N-3) = 5$. For the frequency-sweep map, the fit gave f_r of 906.3 ± 0.2 kHz and w of 3.5 ± 0.2 kHz FWHM with $\chi^2/(N-3) = 7$.

The errors in f_r and w of the frequency-sweep map are again dominated by the frequency sweep's size. Note that, for **bunched** beam, both the f_r and w results from the fixed-frequency map and the frequency-sweep map are consistent. Averaging the fixed-frequency and frequency-sweep results gave $f_r = 906.17 \pm 0.02$ kHz and $w = 3.61 \pm 0.04$ kHz FWHM for **bunched** beam.

Comparing Figs. 1 and 2 shows that **bunching** the beam increased the resonance's width by more than a factor of 2. Moreover, both **bunched** maps show full depolarization over a wide frequency region around the resonance. Also note that, unlike the **unbunched** maps, the two **bunched** maps are consistent with each other in both shape and magnitude. Finally note that the observed **widening** of the **proton** resonance due to bunching is exactly opposite to the earlier observed [11] **narrowing** of a **deuteron** resonance due to bunching.

In summary, we recently used an rf solenoid to study the widths of rf spin resonances with both **unbunched** and **bunched** beams of 2.1 GeV/c polarized protons stored in the COSY synchrotron. We first ran the rf solenoid at different fixed frequencies near the resonance with the **unbunched** beam. We found only a very shallow possible depolarization dip; this shallowness may be due to the proton beam's large momentum spread. We next made a frequency-sweep map using 400 Hz sweeps centered at different frequencies near the resonance; this greatly enhanced the **unbunched** dip. Then we used the same technique to obtain both fixed-frequency and frequency-sweep resonance maps with a **bunched** proton beam; these **bunched** maps were consistent with each other in both shape and magnitude. We found that the **bunched** maps were more than twice as wide as the **unbunched** map. Moreover, the **bunched** maps showed full depolarization over a wide frequency range near the resonance. This **proton** resonance **widening** due to bunching is exactly opposite to the recently observed **deuteron** resonance **narrowing** [11] due to bunching.

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